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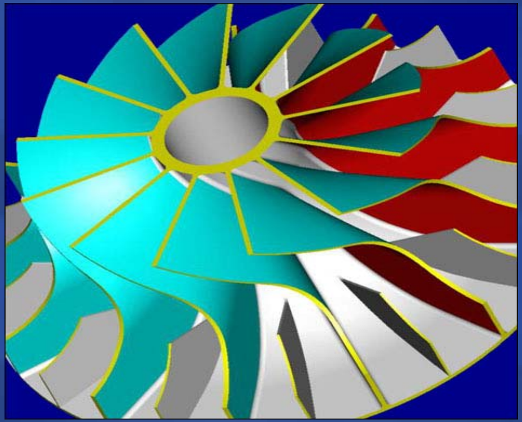
Using Behavioral Modeling to Build Smart Parts that Design Themselves



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Principal

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Outline

What it's NOT

- A flashy sales demo of Behavioral Modeling
- A complex statistical analysis presentation

What it is

- A status of the current design and simulation state in the product development process
- Overview of the tools and techniques for traditional and robust design (DOE, PDS, BMX, Six-sigma, design synthesis, etc)
- An overview of the "Engineering Quality into the Design"
- Implementation examples of Behavioral Modeling
- Overview of the implementation challenges and solution strategies to overcome them

Acknowledgments

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- NAE / NASA Study on product development
- DOE Office of Transportation Technologies (DFV)
- NREL Center of Transportation Technologies & Systems
- FORD Motor Company (CAE Methods Development Group)
- NASA Ames (Integrated Systems Technologies Branch)

for their financial support and technical contributions and source of information

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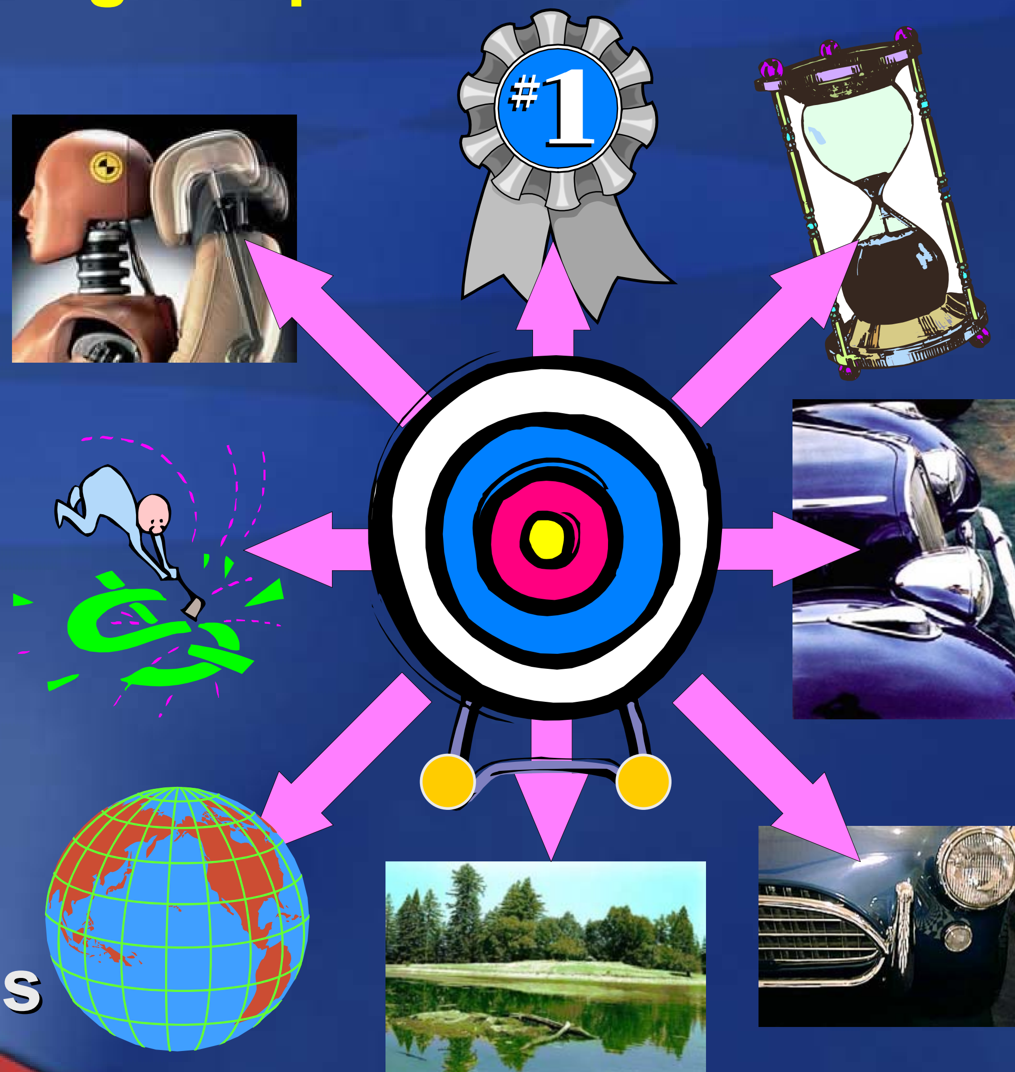
Contradicting Design Requirements

The need for innovative tools is apparent now more than ever as more complex design requirements are surfacing such as:

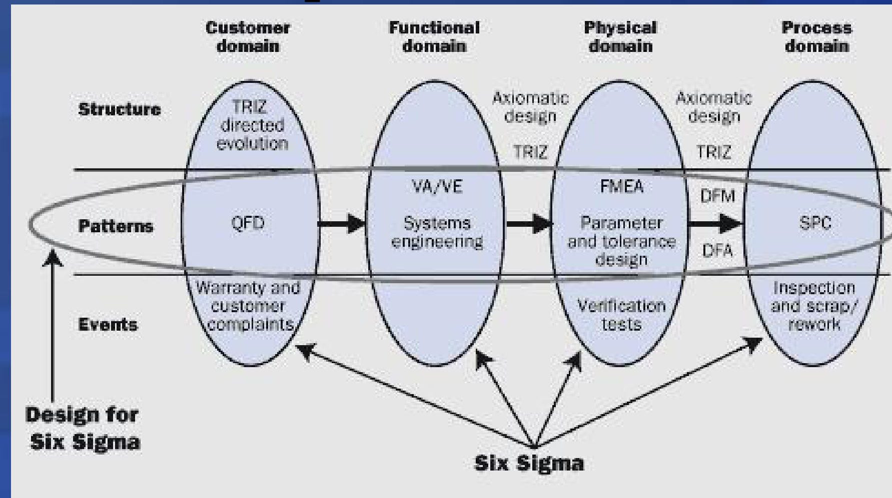
- Cost
- Performance & safety
- Quality
- Time to market & short life cycle
- Environmental impacts
- Wow Aesthetics (creating waves of lust for the product, I got to have it ...)
- Major Changes in Industry's Business Model



Changes in Automotive Industry's Business Model

- Cycle development time from concept to production is being compressed significantly
  - 1992: 60 months
  - 1996: 48 months
  - 2000: 18 months
- Vehicle designs are tailored to focused markets
- Vehicles are being manufactured more on a global scale
- Vehicles designed increasingly through multiple engineering sites around the world
- Need for enabling companies throughout the supply chain and extended enterprise to share information through a web-centric visualization approach

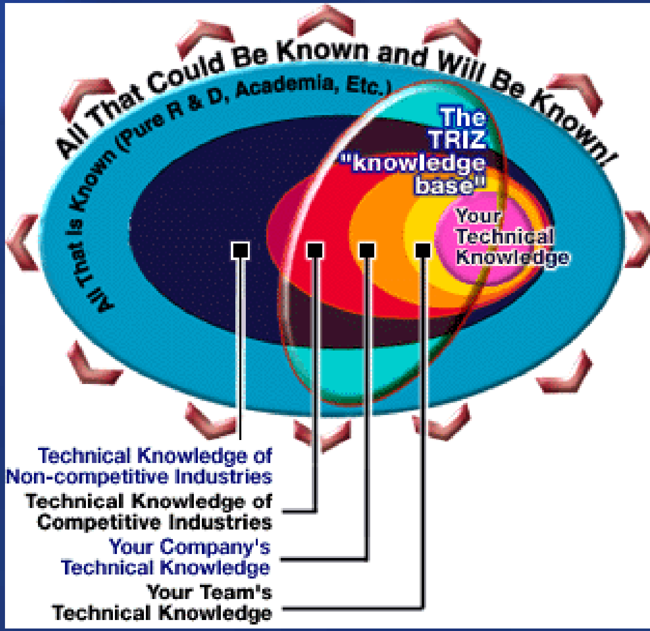
Elements in Product Development Process



- Concept Development
- Product Design
- Attribute Refinement
- Design information systems
  - Knowledge capture and reuse
  - Self designed parts
  - Documentation of rationale for the design
  - Collaborative design

Concept Development

- Typical Elements
  - Conceptual design generation is highly iterative & mostly manual
  - Inconsistent use of heuristics, rules of thumb
  - Success requires experienced skilled practitioners
- Possible Today
  - TRIZ, Functional Diagrams
  - Material-process-section selector
  - Topology optimization
  - Rapid Prototyping

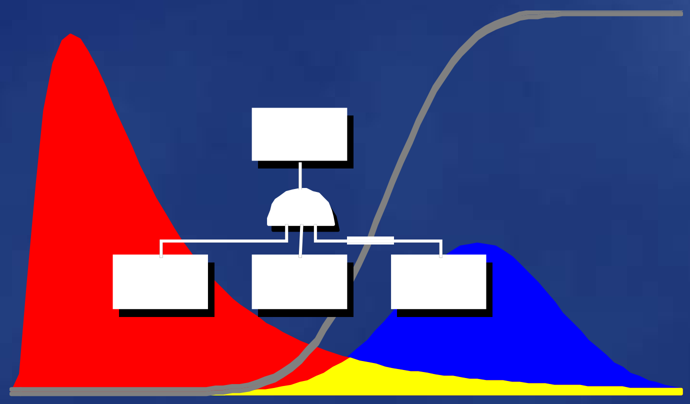


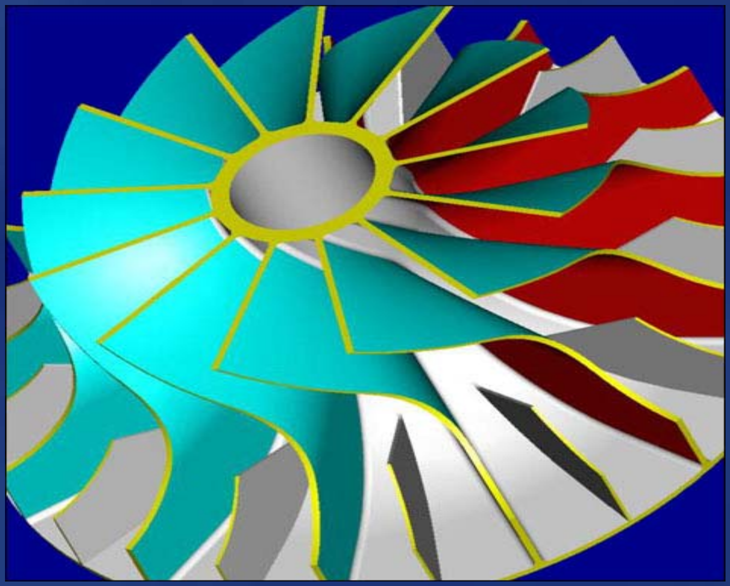
Elements of Product Design

- Rapid generation of design alternatives (CAD, tolerance / variational analysis)
- Process is CAD centric and highly iterative
- Easy evaluation of candidate designs (FEA, CFD, Multi-physics)
- Rigorous evaluation and comparison of design alternatives
- Nonsystematic decision making, many design decisions are based on aggregation of preferences
- Limited reuse of product designs
- Success requires experienced skilled practitioners

Attribute Refinement

- Typical Elements
  - More than half of attributes require experimental refinement
  - Physical prototypes required
- Possible Today
  - Sensitivity and optimization studies of designs
  - Robust Designs (DOE, BMX, PDS, Six-sigma)
  - Reliability based optimization





Expectations
of CAD & CAE implementation

- Reduced Prototypes and testing
- Better integration with suppliers
- Increased reuse of existing designs
- Early prediction of product attributes
- More program predictable results
- Knowledge capture and reuse

Results
of CAD & CAE implementation

- Sporadic demonstrations not sustained benefits
- Best reduction in design and development cost 75% with 2x product complexity
- Typical reduction in design and development cost 5-10% with 2-3x product complexity
- Still tradition and experience govern the design choices

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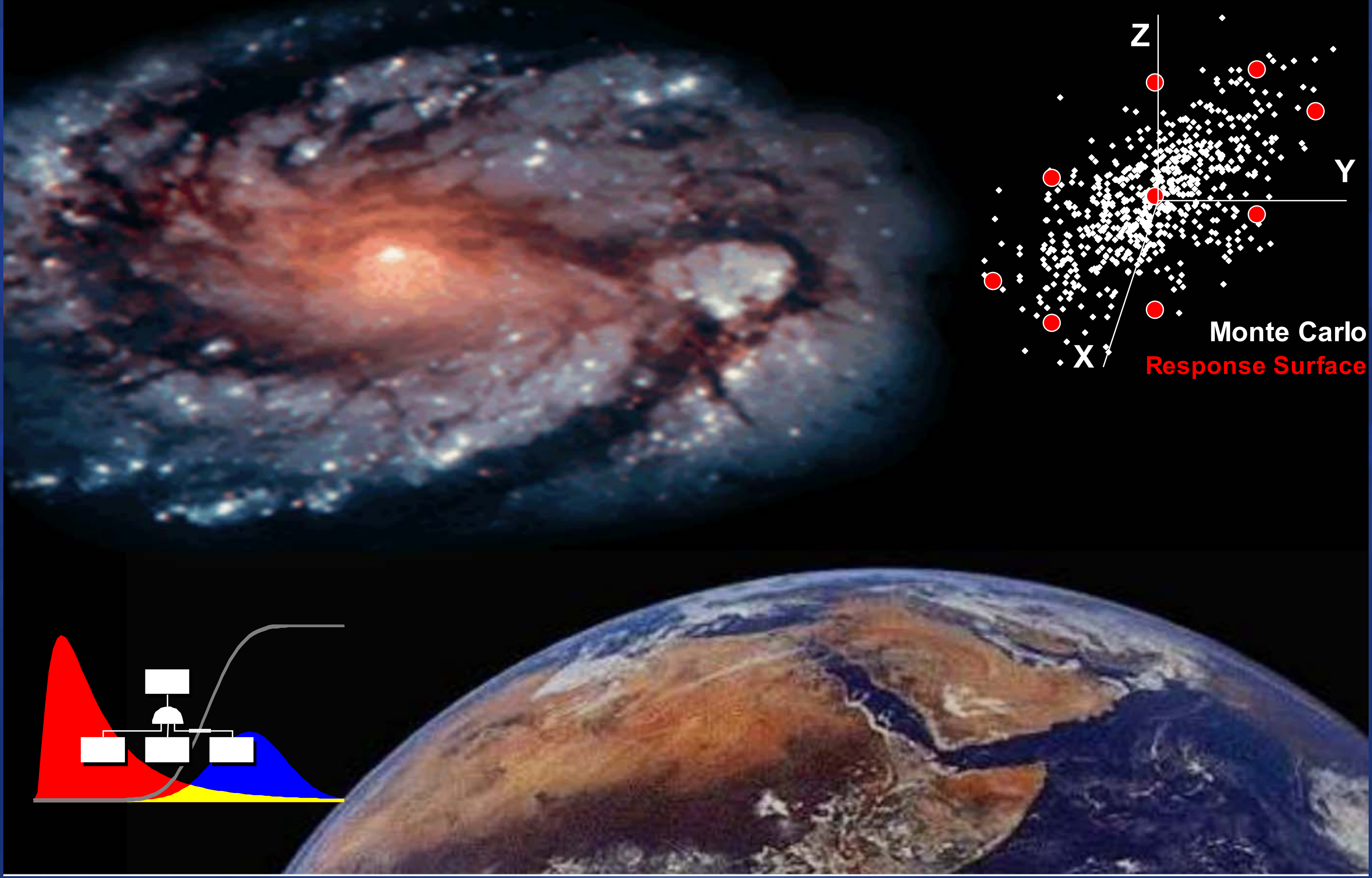
Quality - Robust Design

- **Definition** of Robust Design: Deliver customer expectations at profitable cost regardless of:
  - customer usage
  - variation in manufacturing
  - variation in supplier
  - variation in distribution, delivery & installation
  - degradation over product life
- **Goals** of Robust Design (shift and squeeze)
  - Shift performance mean to the target value
  - Reduce product's performance variability

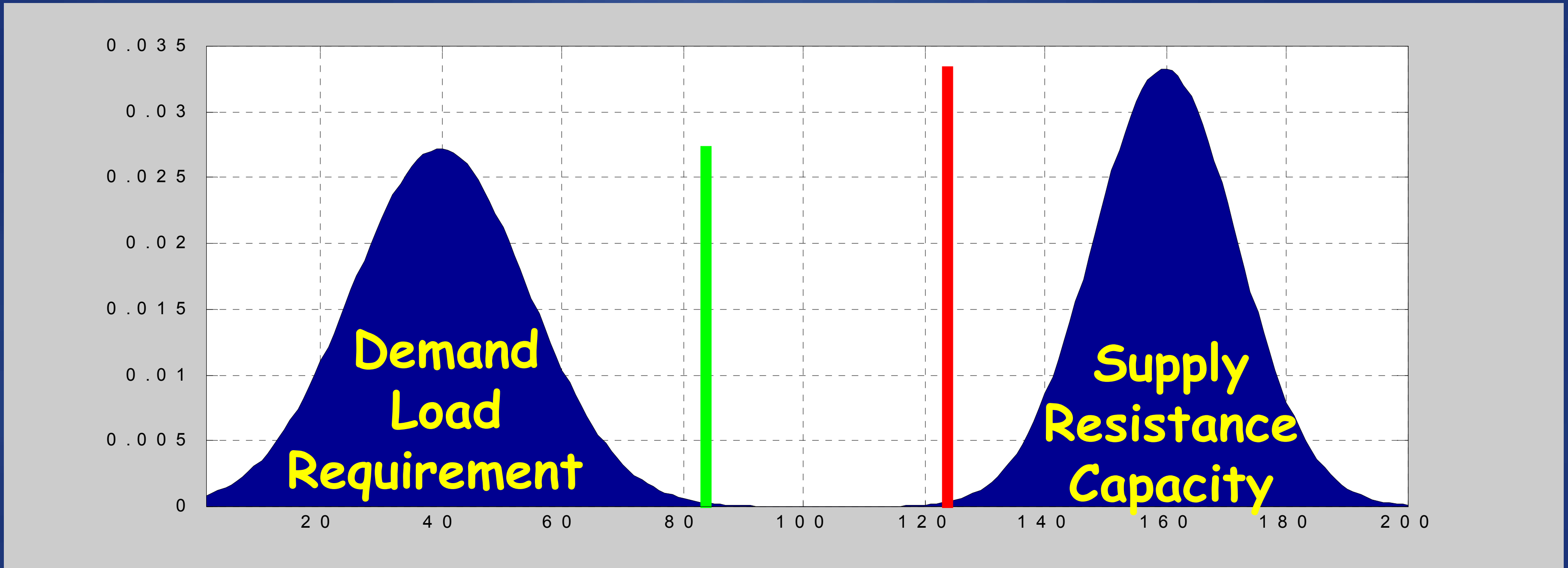


Randomness and Scatter is a part of reality Everywhere

Probabilistic Design Techniques bring simulation closer to REALITY!

Traditional Deterministic Approach

- Accounts for uncertainties through the use of empirical safety factors
- Safety factors:
  - Are derived based on past experience
  - Do not guarantee safety or satisfactory performance
  - Do not provide sufficient information to achieve optimal use of available resources



Statistical Design Performance Simulation

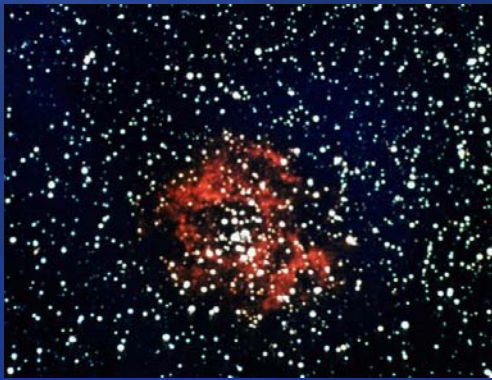
- *" Product quality requires managerial, technological and **statistical** concepts throughout all the major functions of the organization ..."*
  - Josheph M. Juran

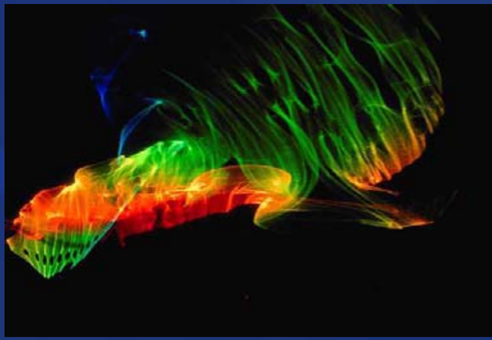
Variation (thickness, properties, surface finish, loads, etc.) is ... *THE ENEMY*

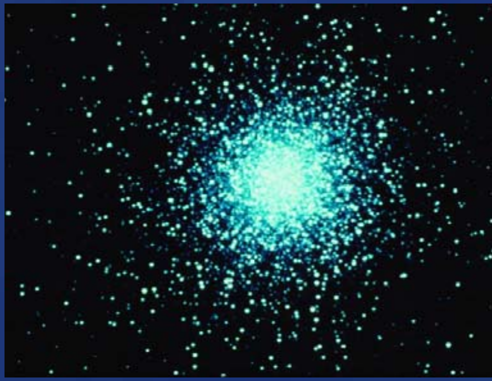
DOE, Six Sigma, Statistical FEA, Behavioral Modeling ... *THE DEFENCE*

Tools for Robust Design

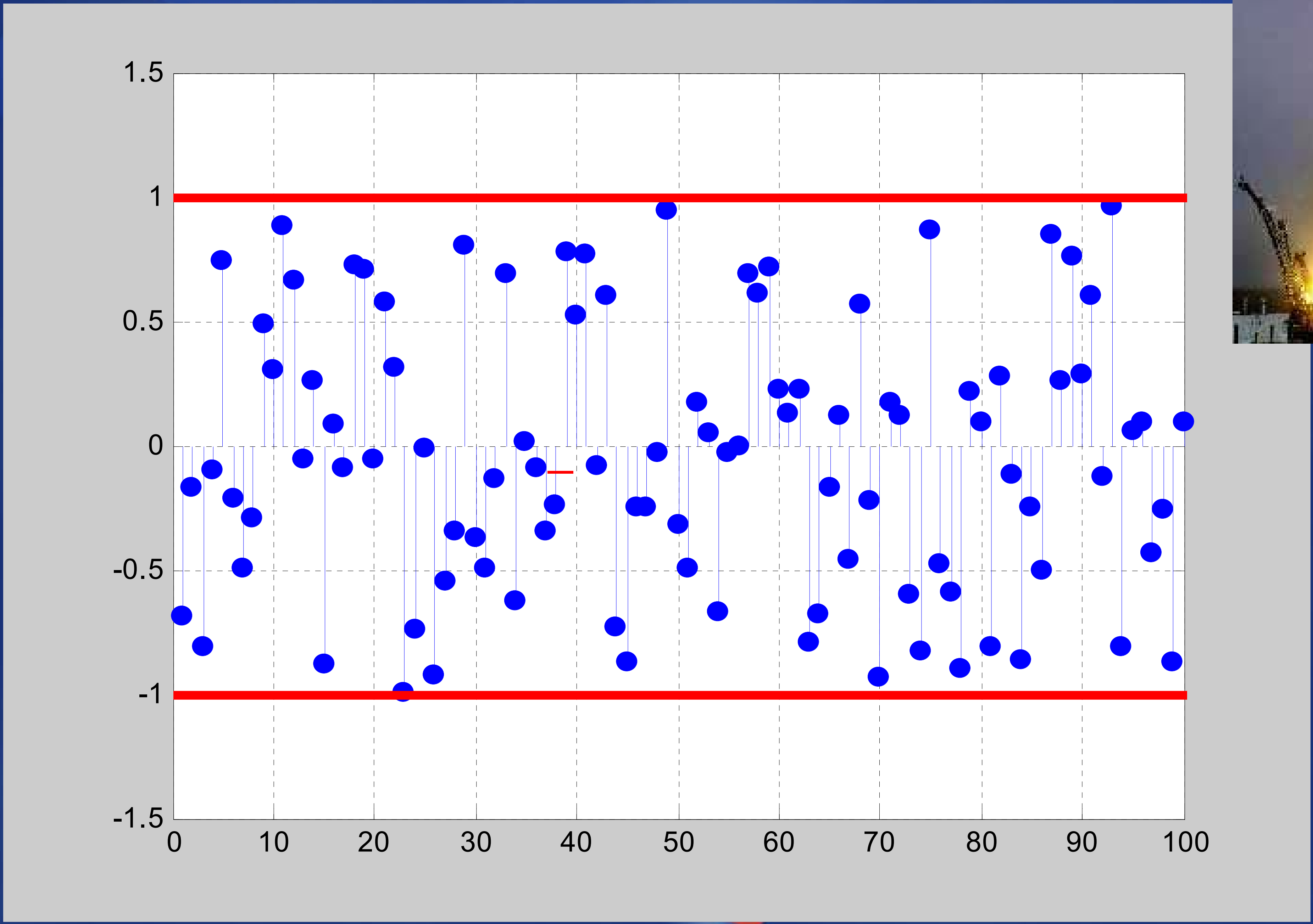
- Design Of Experiments (DOE)
  - Exploits nonlinearities and interactions between noise & control parameters to reduce product performance variability
  - full factorial, fractional factorial, Monte-Carlo, LHC
- Response Surface Methods
  - Central Composite Design
  - Box-Behnken Design
- 6-sigma design (Statistical Performance)
  - Identifying & qualifying causes of variation
  - Centering performance on specification target
  - Achieving Six Sigma level robustness on the key product performance characteristics with respect to the quantified variation



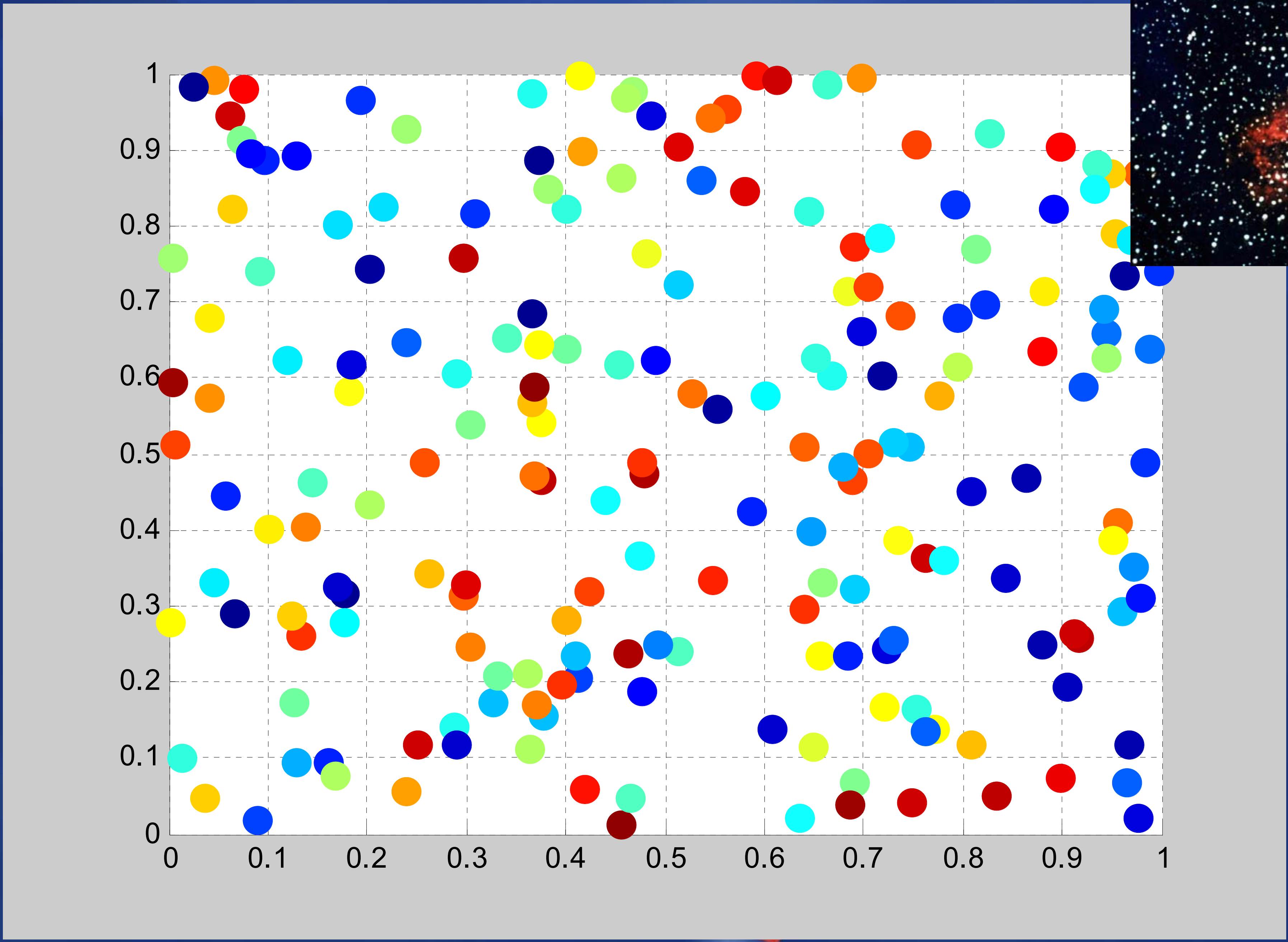




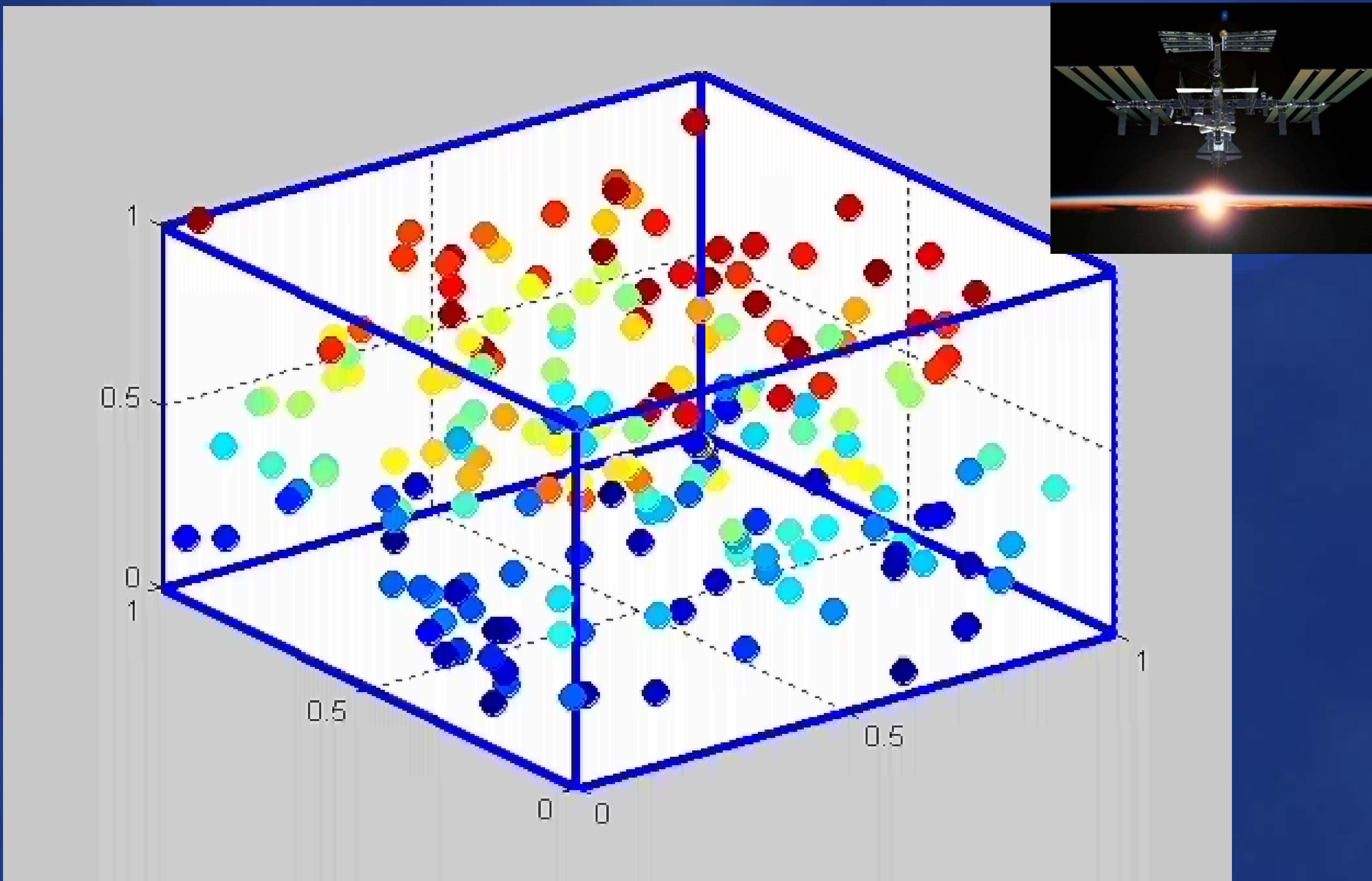
Design Space Exploration 1 Variable



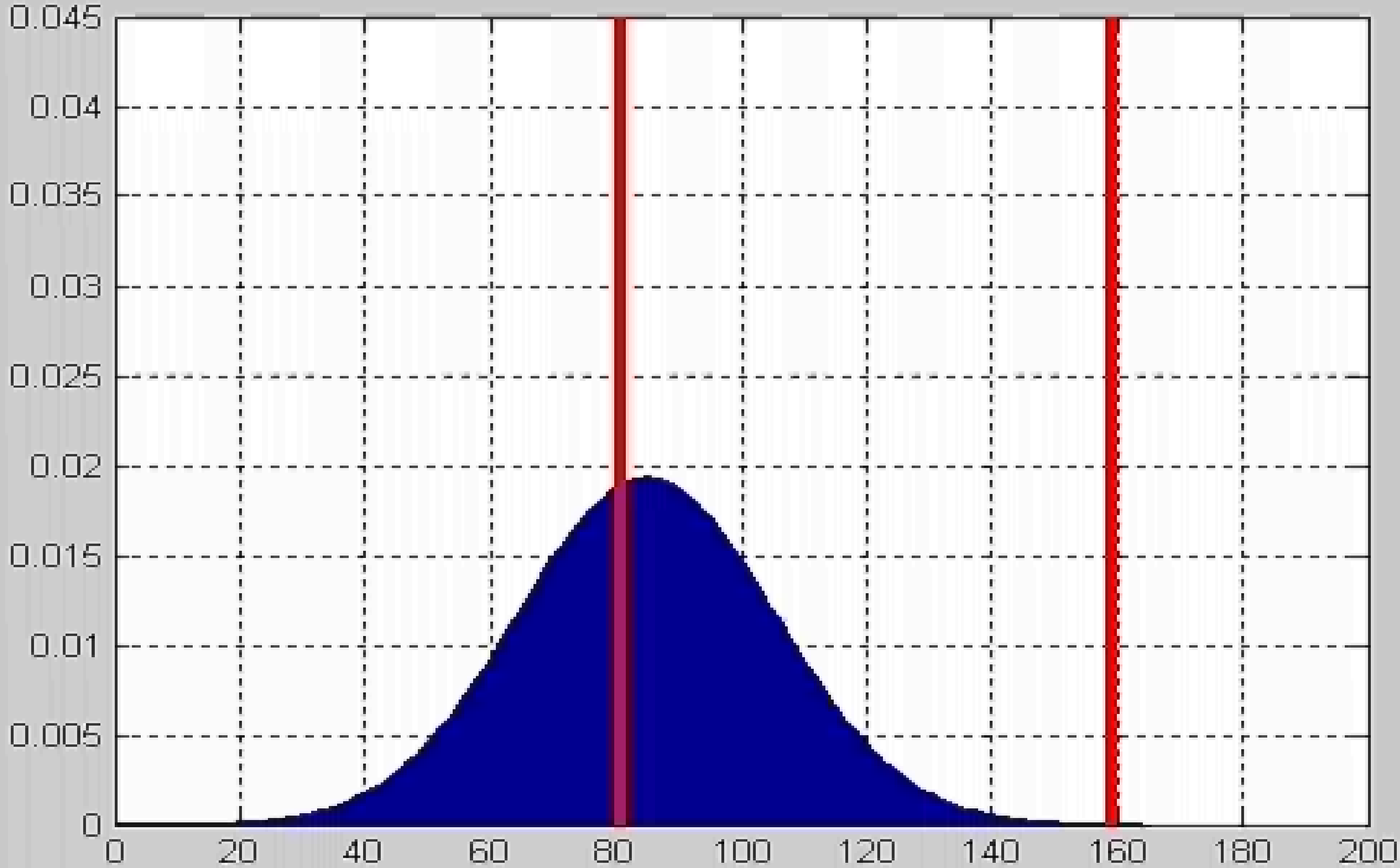
Design Space Exploration 2 Variables



Design Space Exploration 3 Variables



Statistical Performance: Shift and Squeeze



Improved Quality Reduced Total Cost

Cost of Defect or Failure

- Lost Customers
- Liability
- Recalls
- Rework

Examples:

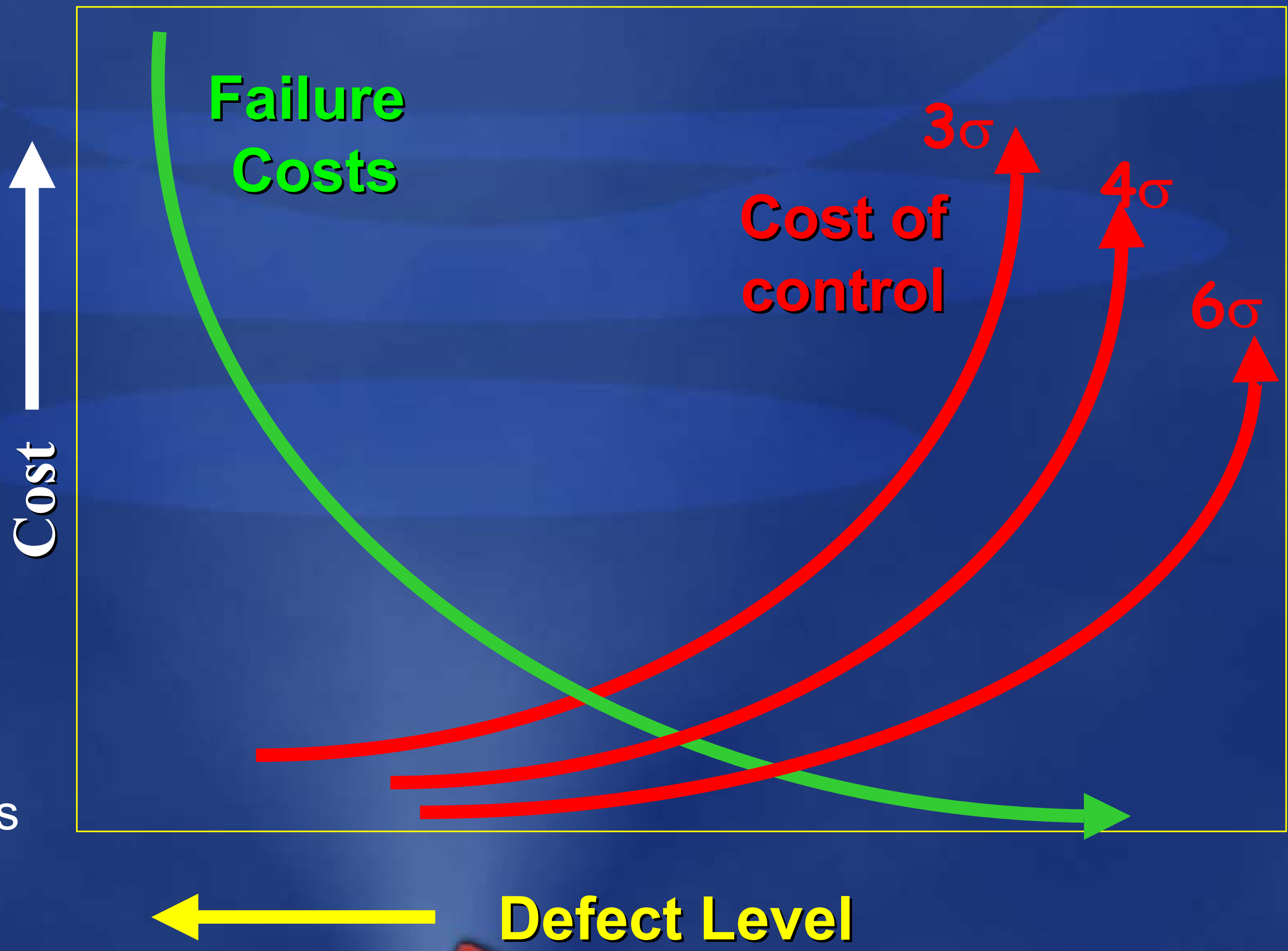
Titanic

Asbestos

Breast Implants

Bhopal, India

…



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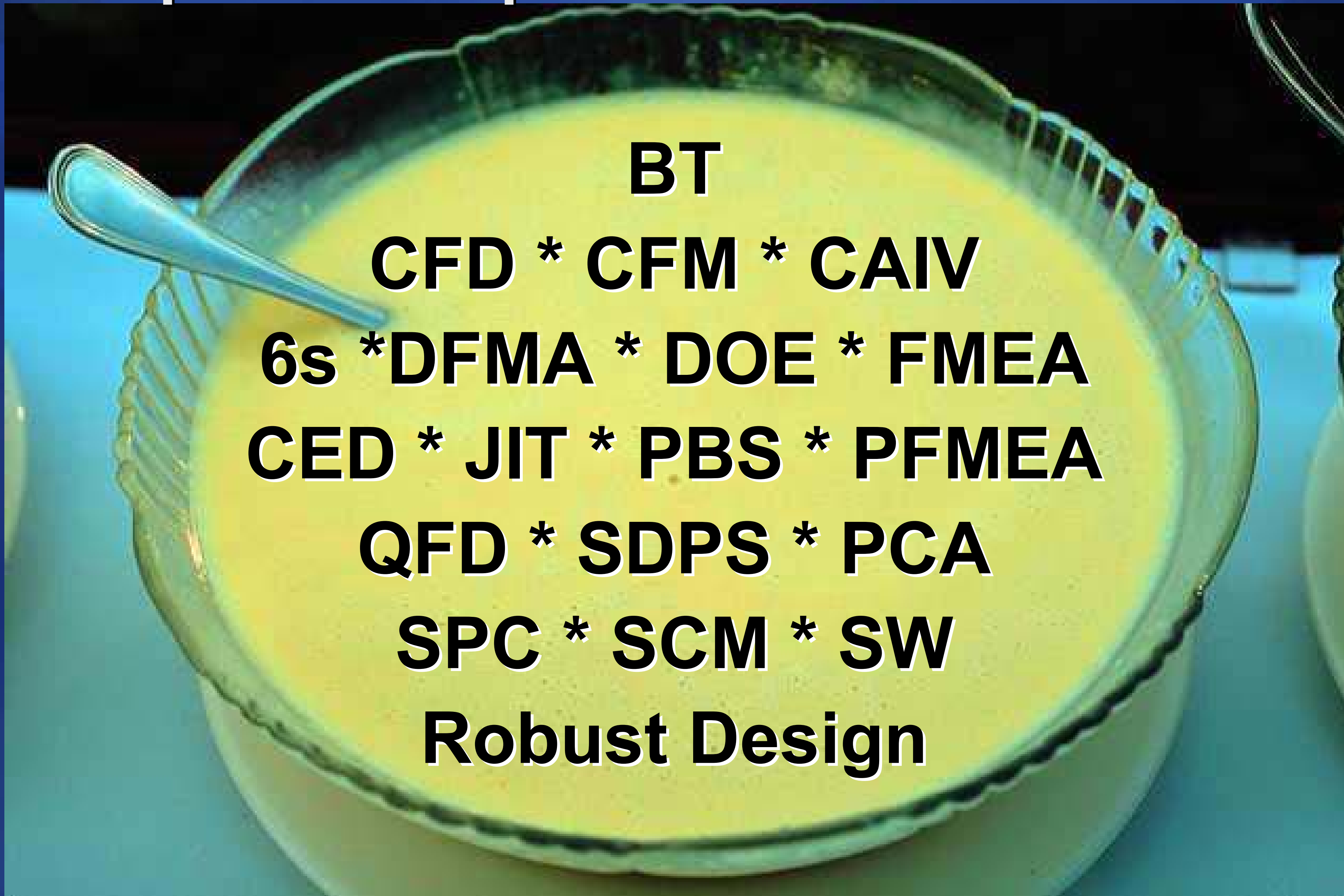
Elements of Quality Management Process

- Agile Improvement Process
- Axiomatic Design
- Benchmarking & Bench-trending
- Catch-ball
- Cellular Manufacturing
- Continuous Flow Development
- Continuous Flow Manufacturing
- Cycle Time Management
- Defect Reduction
- Design for Manufacturing and Assembly
- Design of Experiments
- Failure Modes Effects Analysis
- Cause and Effect Diagrams
- Just In Time
- Performance Based Specifications
- Process Failure Mode Effects Analysis
- Quality Function Deployment
- Robust Design
- Self-Directed Work Teams
- Statistical Design Performance Simulation
- Process Capability Analysis
- Statistical Process Control
- Supply Chain Management
- Synchronous Workshops
- Theory of Constraints
- Thinking Process Reality Trees
- Total Productive Maintenance

Elements of Quality Process:
The alphabet soup

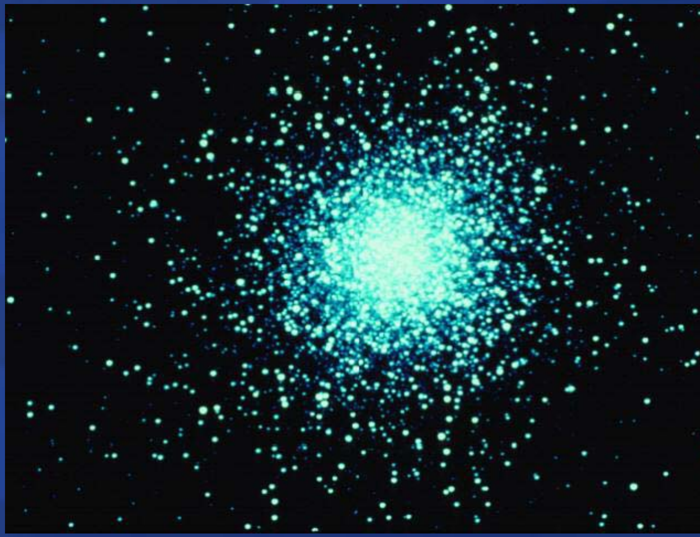


Elements of Quality Management Process

- Although all the elements of quality management process are closely connected they remain apart because they have been developed independently from each other
- Integration of these tools is critical to the organization and necessary for successful federation and robust optimization efforts

Identifying Noise & Control Parameters

- Noise parameters:
  Factors that are beyond the control of the designer
  - material property variability
  - manufacturing process limitations
  - environment temperature & humidity
  - component degradation with time
  - ...



- Control Parameters:
  Factors that the designer can control
  - geometric design variables
  - material selections
  - design configurations
  - manufacturing process settings
  - ...

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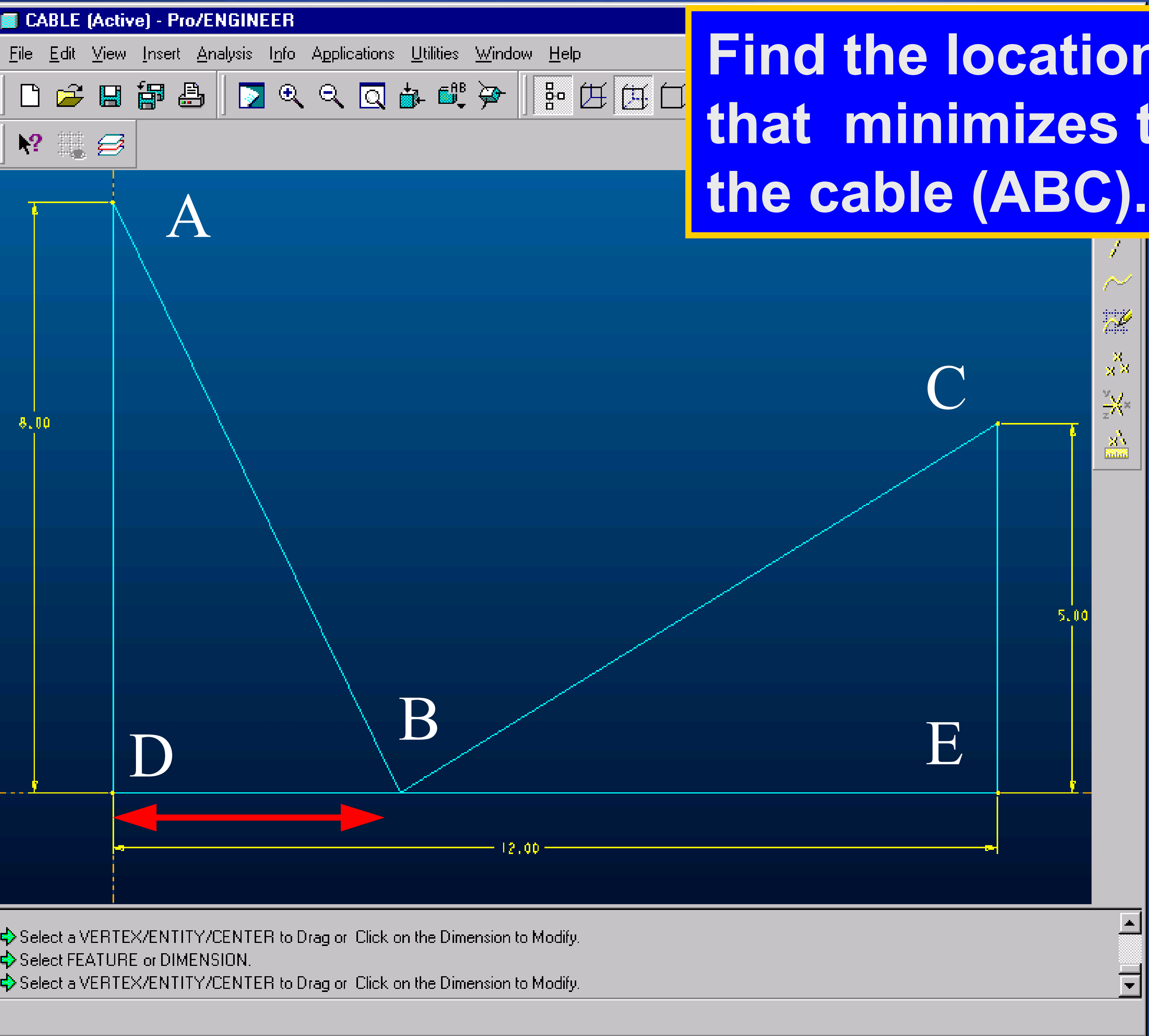
Implementation Examples of Behavioral Modeling

1. Cable length optimization
2. Requirement Driven design
3. Inspection of thickness requirements in castings
4. Packaging optimization of metal stamped parts to minimize scrap
5. Design criteria driven column design (a smart self designed part)
6. Reliability based design within Pro/Engineer

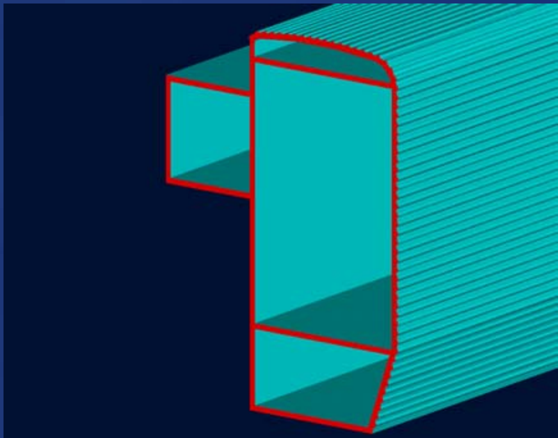
Example # 1 Cable length minimization

Find the location (distance DB) that minimizes the length of the cable (ABC).



Example # 2
Behavioral Modeling of the Section

- All sections have the same moment of Inertia
- Find the one that minimizes the cross sectional area (Min Weight) and meets all the manufacturing and stability requirements
- Not a dimension driven CAD model
- Requirement driven design (I_{req})



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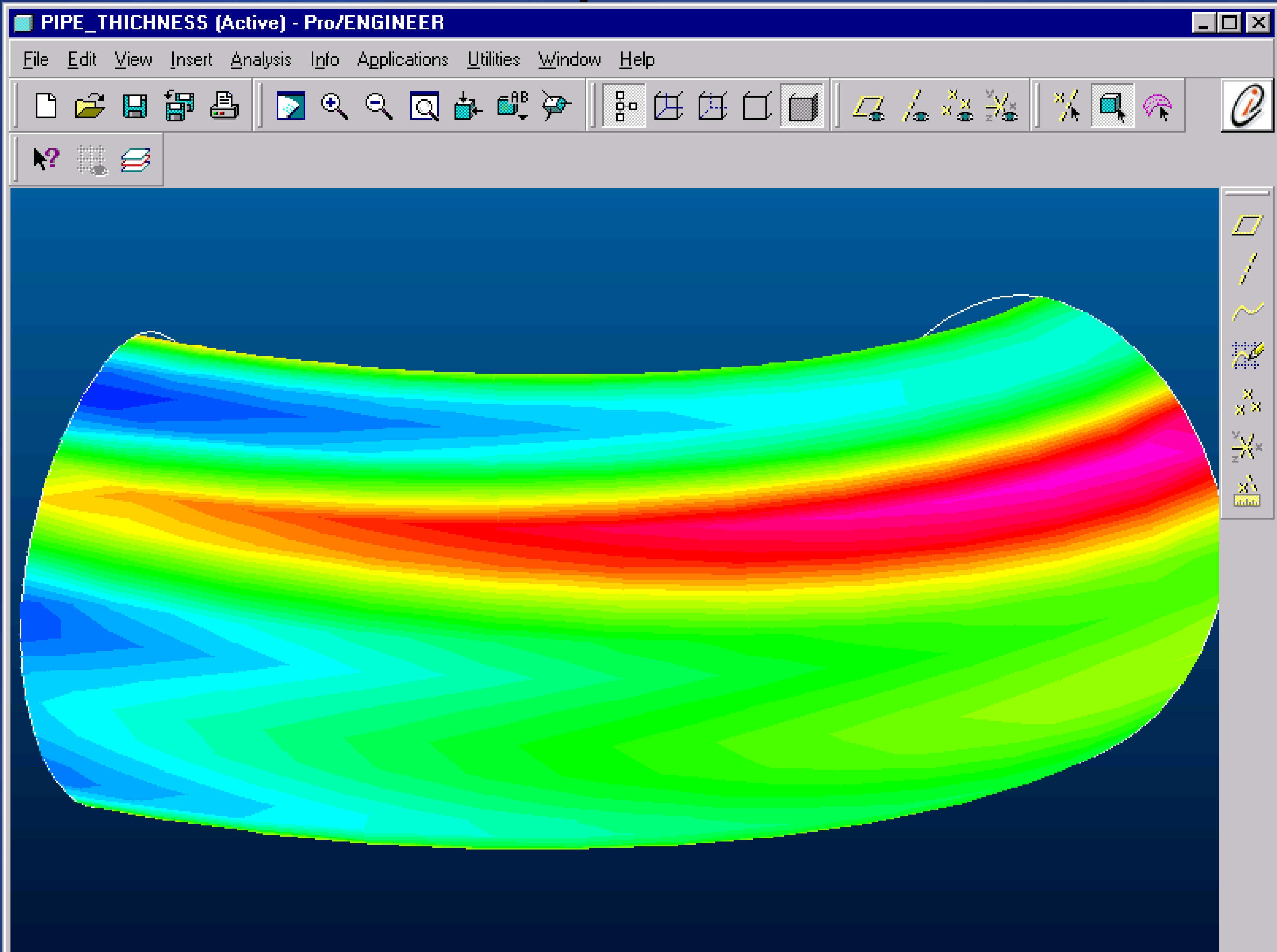
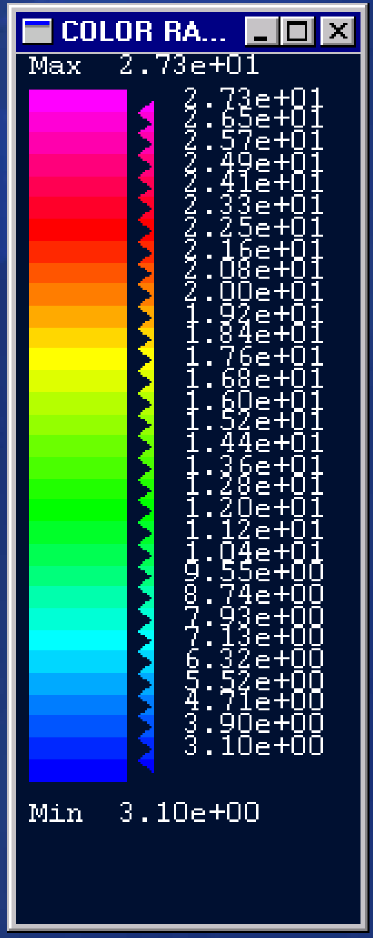
Example # 3 Thickness Distribution

Inspect the cast pipe for minimum thickness requirement

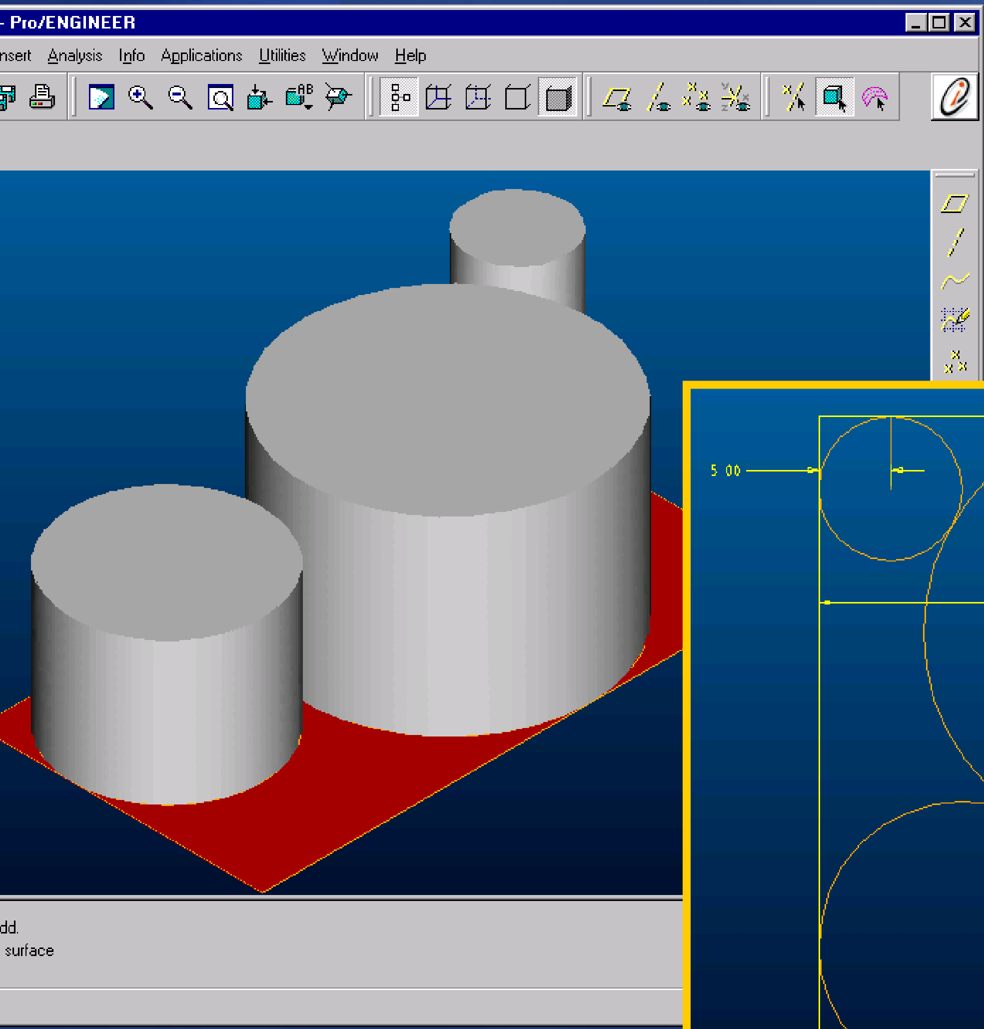


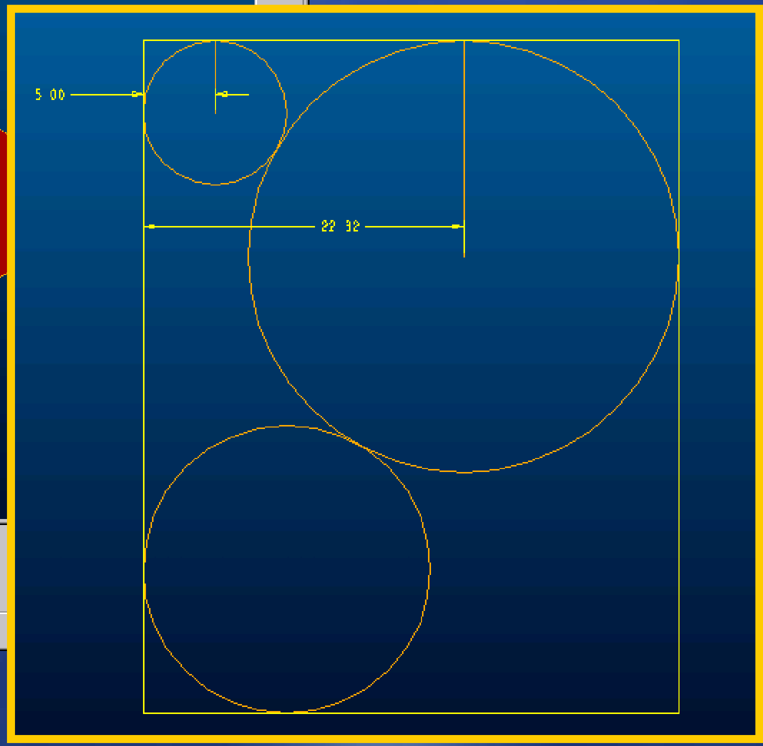


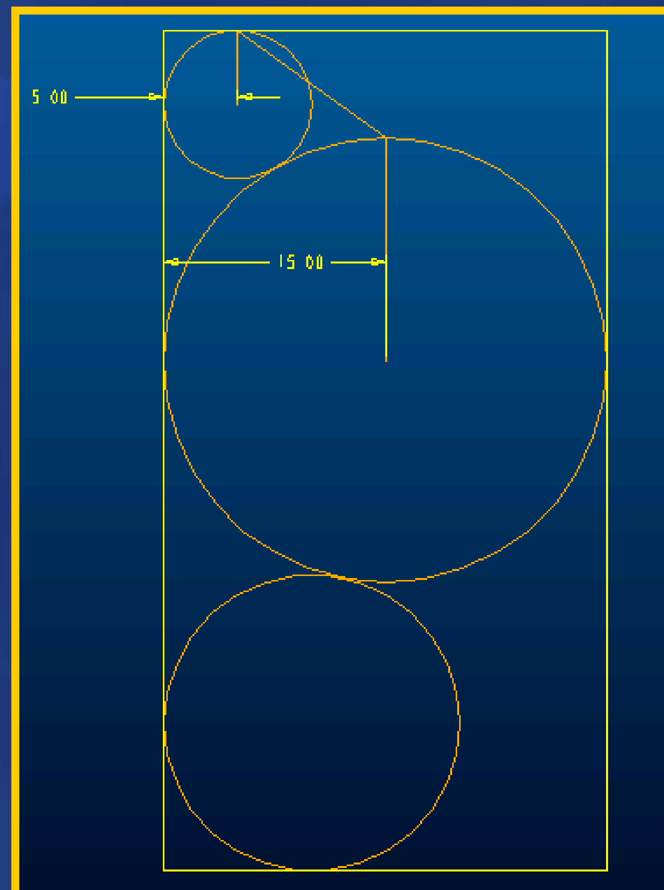
Example # 4 Packaging Optimization

Arrange the objects such that the circumscribed rectangle has:

- minimum projected area
- minimum perimeter
- minimum container surface area







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Example # 5 A Self Designed Column

- Design Variables
  - R = mean radius of the column
  - t = wall thickness
- Design Constraints
  - The maximum compressive stress should be less than the allowable σ_a
  - The column should not buckle under the applied factored load P
- Objective
  - Minimize the weight of the column

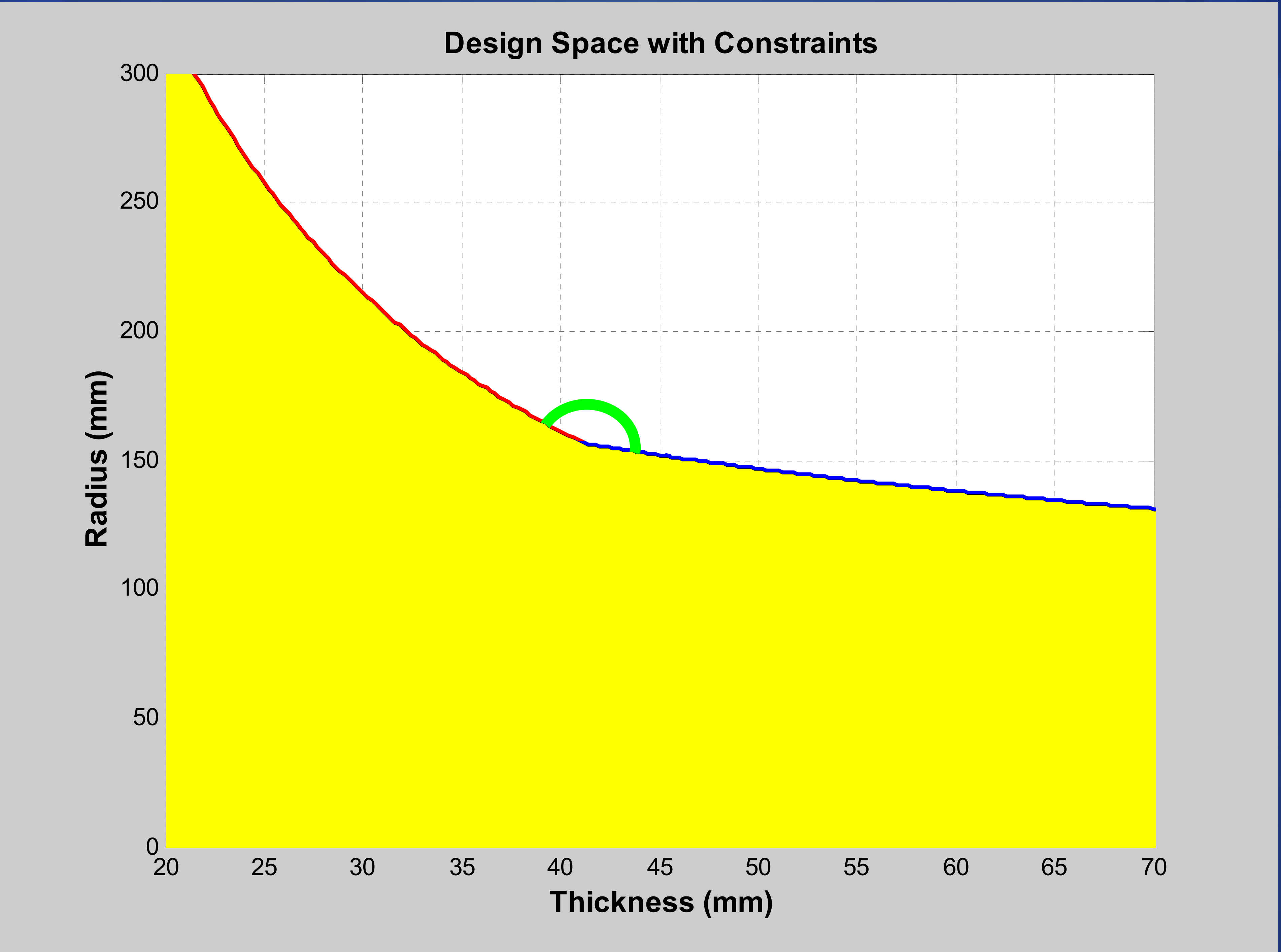
Formulation of Design Constraints

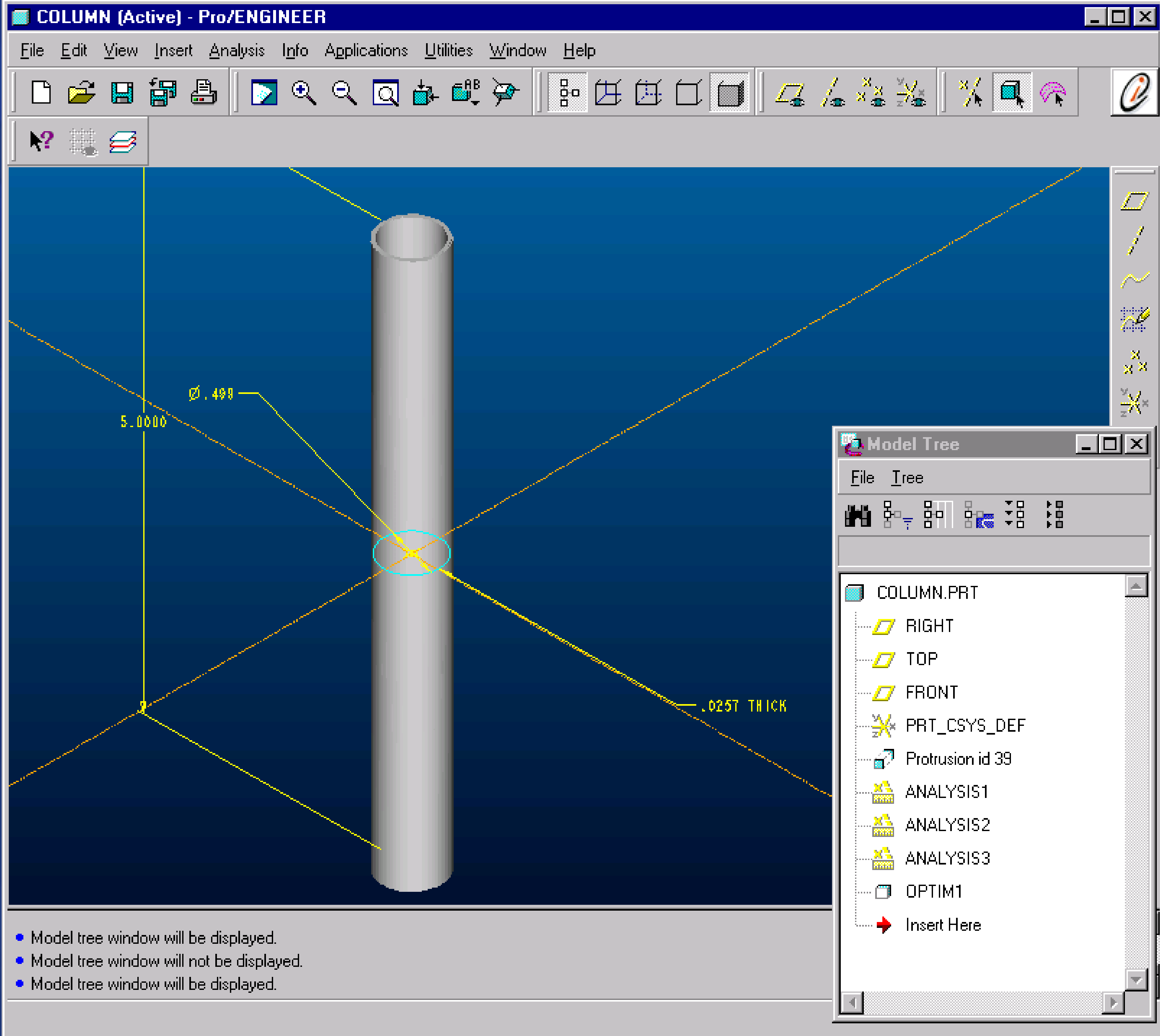
Feasibility Constraint: $R \geq 2 * t$

Buckling Load Constraint:
$$P \leq \frac{\pi^2 EI}{(kL)^2} \Rightarrow I \geq \frac{P(kL)^2}{E\pi^2}$$

Maximum Compressive Stress Constraint:
$$\frac{P}{A} \leq \sigma_a \Rightarrow A \geq \frac{P}{\sigma_a}$$

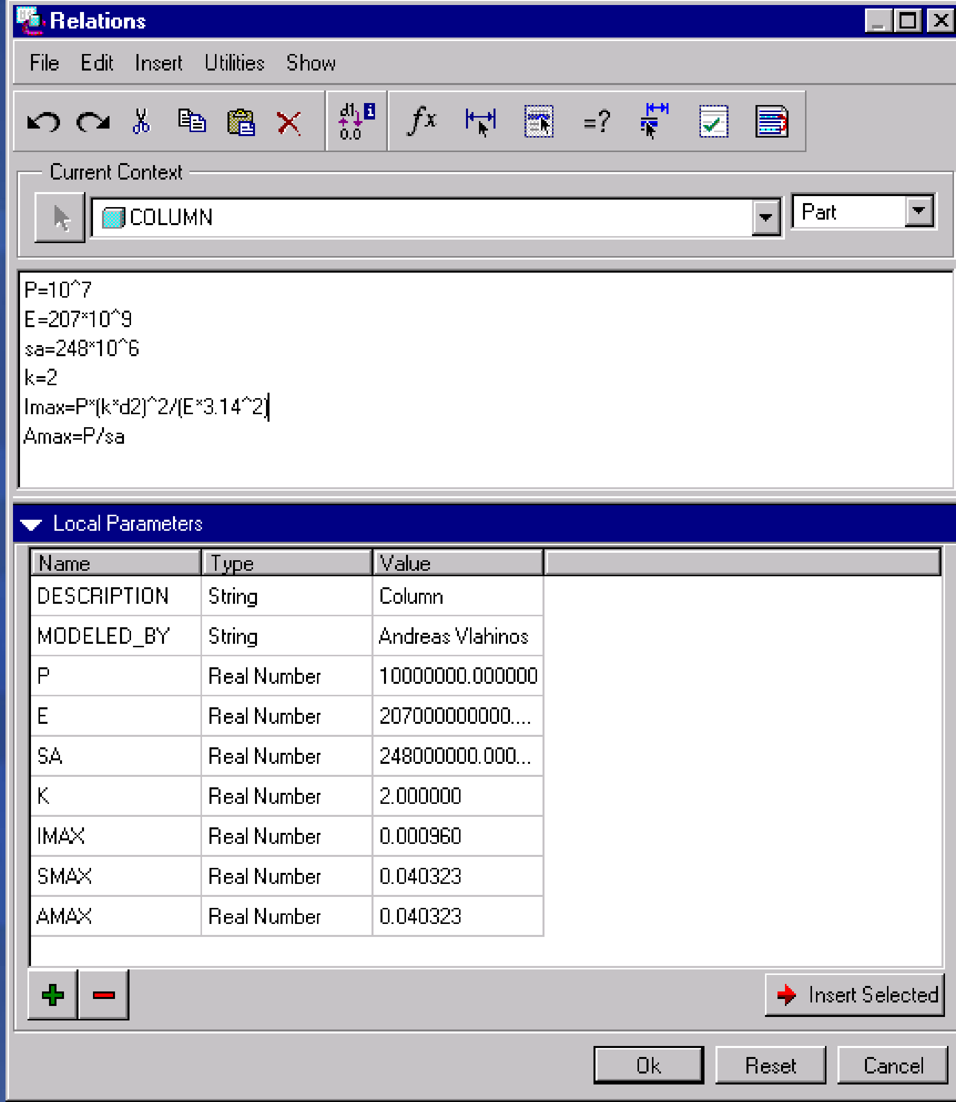
Design Space -Traditional Solution




COLUMN (Active) - Pro/ENGINEER
File Edit View Insert Analysis Info Applications Utilities Window Help
Ø.499
5.0000
.0257 THICK
Model Tree
File Tree
COLUMN.PRT
RIGHT
TOP
FRONT
PRT_CSYS_DEF
Protrusion id 39
ANALYSIS1
ANALYSIS2
ANALYSIS3
OPTIM1
Insert Here
Model tree window will be displayed.
Model tree window will not be displayed.
Model tree window will be displayed.

Relations

- P=10^7
- E=207*10^9
- sa=248*10^6
- k=2
- Icr=P*(k*d2)^2/(E*3.14^2)
- Acr=P/sa



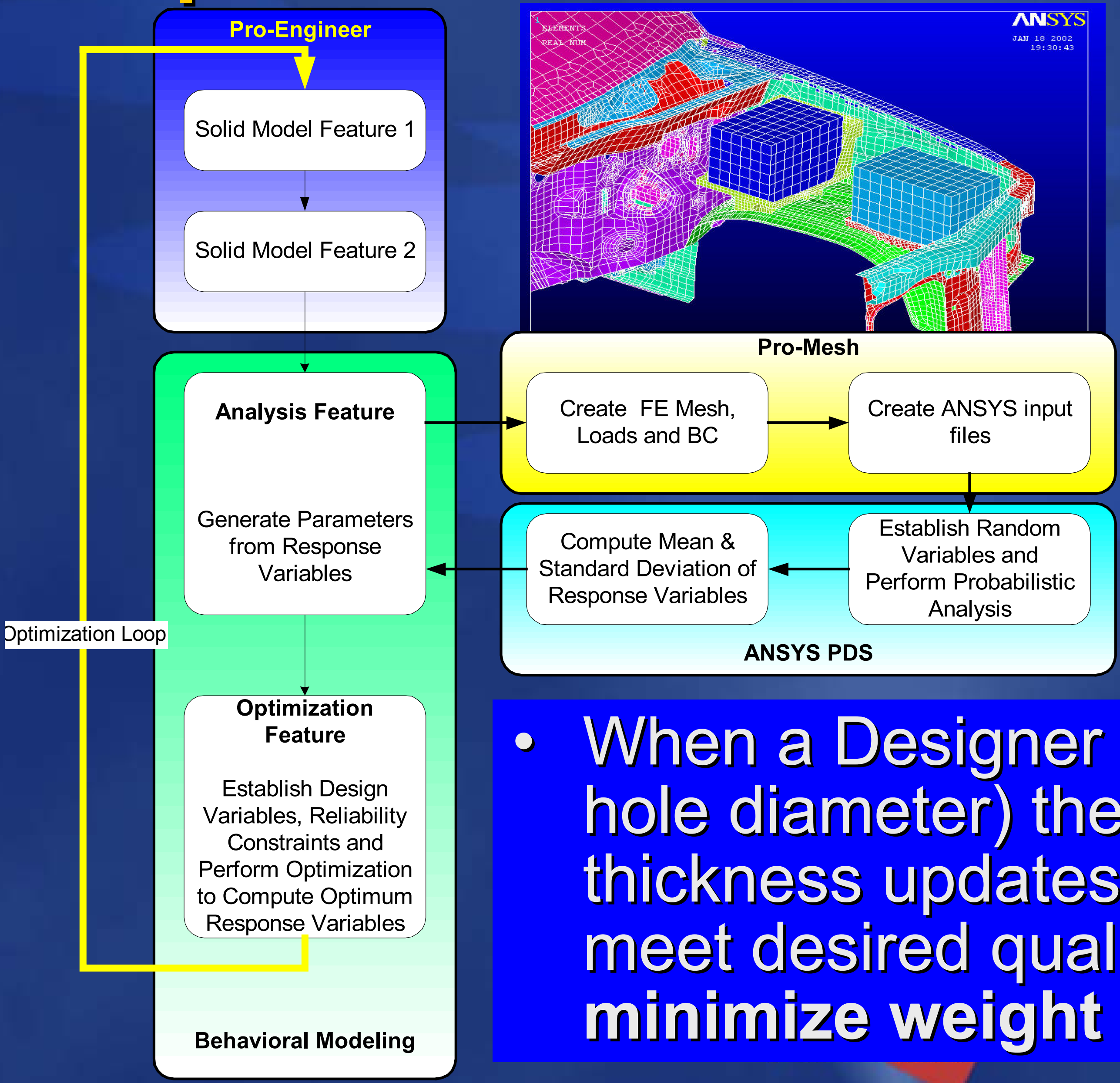
Analysis3 Feature relation:

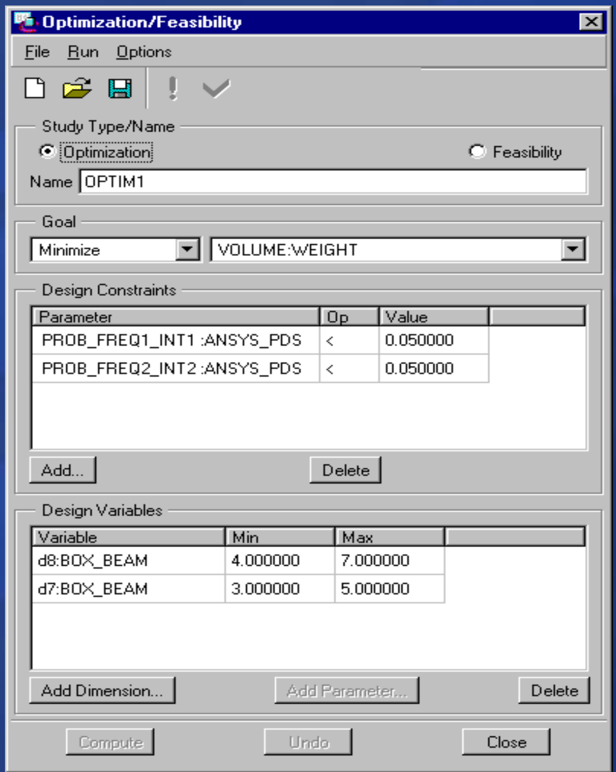
cons_1=xsec_area:FID_ANALYSIS1-Acr

cons_2=xsec_inertia_1:FID_ANALYSIS1-Icr

Example # 5

Workflow for Reliability Based Optimization within Pro/Engineer





- When a Designer makes a change (i.e. hole diameter) the component thickness updates automatically to meet desired quality criteria and **minimize weight**

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Why not realizing the expected gains from a CAD & CAE integration?

- Technical challenges
  - Design process remains unstructured or unplanned
  - Insufficient number of experts for product design & attribute prediction
  - Product attributes have not been formalized and managed early enough
  - CAD / CAE toolset is not tailored to design environment
  - Data not readily available to feed analysis

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Why not realizing the expected gains from a CAD & CAE integration?

- Organizational challenges
  - Lack of clear metrics and success stories
  - Achieving consensus on methods to be used and on integration of product development environment with PDM software
  - Developing and implementing custom capabilities with commercially available software (BMX, Visual DOC, iSIGHT,AI*workbench,CO,…)
  - Organization's commitment to product development excellence

Realizing The Expected Gains

1. Identify the right organization
   - Committed to product development
   - Willing to change
   - Able to make decisions
   - Willing to bypass consensus where needed

2. Identify the right project
   - Repetitive and measurable
   - High value added
   - Bottle neck, short duration (3-6 months)
   - Non trivial, expertise required
   - Mainly with objective requirements

3. Solution Strategies

- Clarify and document the desired design decision process
- Establish the cost & time of the current state
- Create a design environment tailored to the desired design process; workflow management
- Develop a repository of design & manufacturing rules to govern the design process
- Augment the experts by automating large portions of the design process (BMX)
- Simplify and automate tool usage for standard analyses
- Improve attribute prediction as knowledge increases
- Automate data integration and allow for new methods

Create a Vision,

Adopt it,

Adapt to Achieve it